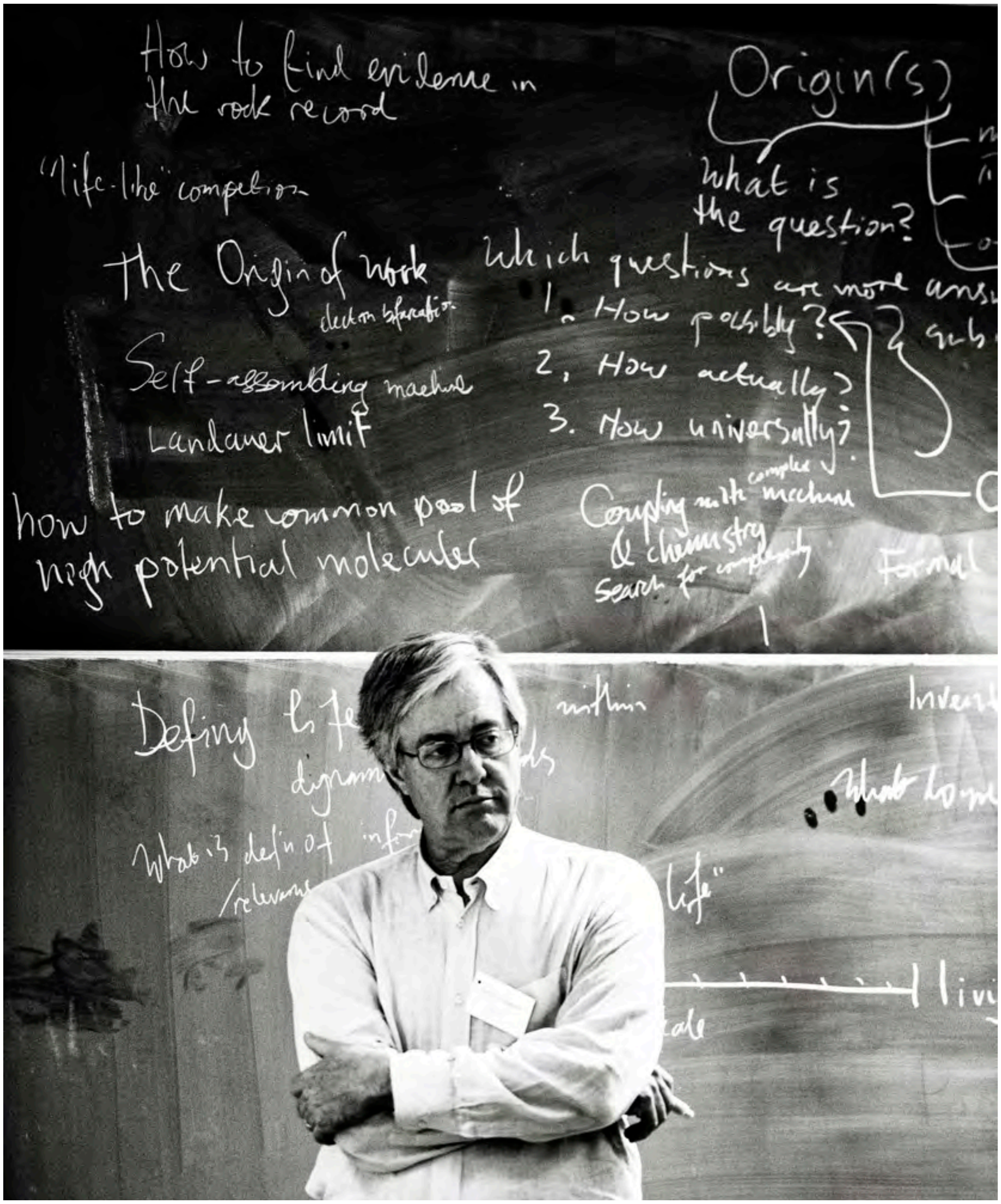


Norman Packard of Protolife leads a wrap-up discussion at the inaugural ELSI Origins Network workshop, which set out to draw a roadmap for Origin of Life research. He is one of the international Origins collaborators brought to ELSI through the EON long-term visitors program.

8.A Big Grant Brings a Unique New Program

There came a time in the history of ELSI when it became apparent that the institute needed more scientists in the program. They were needed to bring in new ideas, to make the campus itself more vibrant, and to expand the scope of the ongoing science.

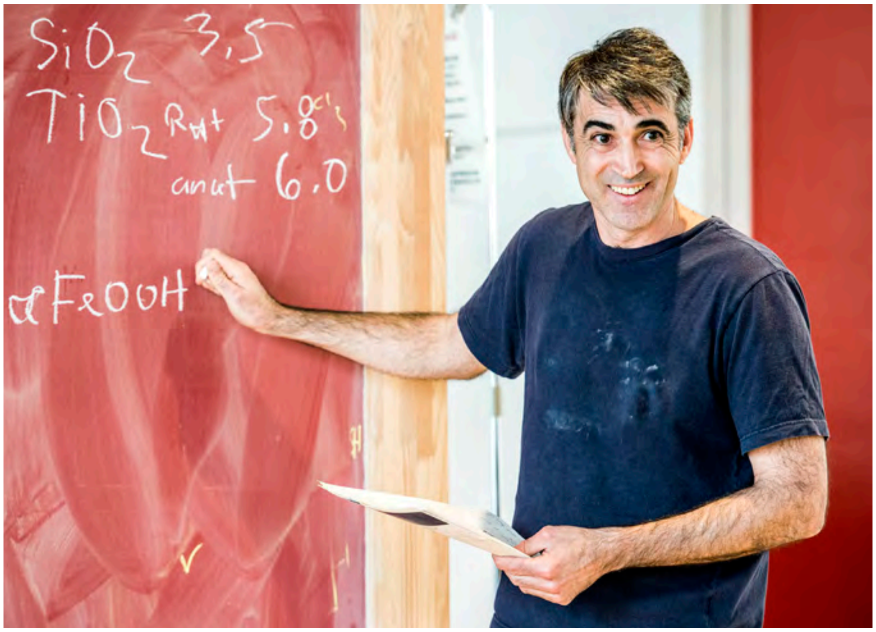
And if there was going to be an expansion, it needed to meet one of the WPI program's key priorities for ELSI and the companion institutes – that the institutes should aim to be as international as possible.

Out of this collection of needs and hopes came the idea for the ELSI Origins Network. Of the many unique initiatives underway at ELSI, the network (EON) is among the most pioneering.

In short, the EON program brings in ten early-career, postdoctoral scientists from around the world. They are hired for two years and required to spend six months a year in Japan and the rest of their time at home institutions.

In return, unlike most postdocs, they have no teaching responsibilities; they are free to dive into the research they think is important in the general origins field or in their own related disciplines; and they receive decent compensation and a research budget.

They are from different disciplines, often have some projects they are already working on, and are given great freedom to follow their research into subjects related to the origins of life.



Jim Cleaves, director of EON and one of the founders of the program.

"There is nothing else like EON in our field, maybe in science," says Jim Cleaves, the director of the program and one of the several ELSI scientists who helped set up the program in 2015.

"Clearly, it attracts people who are independent, who are self-starters, and who aren't afraid of living in another culture. This is quite a challenging program, but the results have been positive from all sides."

Of the ten original EON fellows, he says, all have either finished their postdocs, gotten permanent jobs, or are still in the program. Several other fellows have also been added.

Together, they have been integral building blocks in the formation of the species "ELSI."

The logic of EON, as explained by its founders, is not just to bring more researchers to ELSI but also to create and strengthen contacts and collaborations within the global family of scientists working on origin-of-life issues in the broadest sense.

This is a field that has gone from great international interest, especially after the Miller-Urey experiment of the early 1950s showed that chemical building blocks of life could be made from simple compounds and an electric spark, to a position pretty far from the limelight. Some scientists have always pushed forward on this question, which is among the most important and most difficult that exist, and NASA in particular has funded origin-of-life work. But a hot field it is not.

"The community of people who would consider themselves origin-of-life scientists is pretty small," says Piet Hut. "But the community of scientists who work on issues related to origins of life is much larger. Part of our job has been to make those connections more apparent and then bring the scientists together."


EON research scientist Kosuke Fujishima, who has appeared on numerous media programs to talk about astrobiology, said his time at ELSI "was *the* most remarkable and fruitful period of my career being an astrobiologist."

It was Hut, the head of interdisciplinary study at the Institute for Advanced Study at Princeton and an ELSI founding proposer, who made the connections that led to the EON program.

As he tells it, he was at the site of the European Organization for Nuclear Research (CERN) supercollider with other scientists and representatives of the John Templeton Foundation to talk about the facility's immense computing power. The Templeton representatives had a history of supporting origins-of-life and other basic research, and so they asked the assembled scientists if they had projects that might meet the Templeton criteria.

Hut said that nobody but him rose to the challenge, and he proposed what became EON.

"They had found the origin of matter – the Higgs boson – and we are working on the origins of life. I thought it made sense for Templeton, and it certainly did for us."

The $5.6 million, 33-month grant has been used not only to support the EON fellows but also to invite many of the experts in their respective fields to workshops at ELSI through a short-term visitors program for scientists. The goal, again, has been to bring scientists together, to encourage them to collaborate, and then to see what happens.

"Many papers have been published and many more are in the works from the EON fellows," says Cleaves. "But equally important is the way these scientists have taught colleagues around the world about ELSI and our collaborative ways. I would say that for all of them, their experiences here have made them real advocates for ELSI."

This was hardly a simple institutional task. As explained by EON project manager Kyoko Akiyama, the challenges included setting salary payments pegged to a certain U.S. dollar exchange rate which was adjusted every six months; otherwise, the fluctuations could and would be great and the fellows couldn't rely on a set monthly salary. The

Donato Giovannelli, evolutionary microbiologist and extremophile hunter. His home affiliation was the Rutgers Institute of Earth, Ocean and Atmospheric Science.

EON staff also had to clear the postdoc research spending when they were at their institutions outside of Japan. The complications were endless.

"EON program activities challenged many administrative ways of doing things at Tokyo Tech because of the international character of the network building," Akiyama said. And as a member of the World Premier International Research Center program, one of ELSI's formal tasks was to encourage just those kinds of administrative challenges and changes.

To understand the uniqueness and daring of the project, nothing is more helpful than to meet some of the EON fellows.

They range from a computer scientist working to create virtual chemistry, to an evolutionary microbiologist studying the most ancient extremophiles, to a philosopher exploring the nature of cognition and awareness, and to several researchers studying complex prebiotic chemistry and early biology.

They are – in keeping with core ELSI priorities -- a diverse group in terms of their disciplines, their nationalities, and their backgrounds. Since they have to live in Japan for six months and at a cooperating university elsewhere for six months, they clearly have to be flexible people.

Consider, for instance, Kosuke Fujishima. An astrobiologist by training, he spent time at ELSI working on outside-the-test-tube experiments related to planetary science and geochemistry and on setting up collaborations with researchers at JAXA and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) to do scientific groundwork for a potential future sample-return mission to Saturn's intriguing moon, Enceladus.

He also spent six months at the NASA Ames Research Center, where he began experiments on the interplay of proteins and RNA – an important origins-of-life problem. His hypothesis is that proteins and RNA coexisted and coevolved, and he has begun experiments to test it. If the hypothesis is found to be possible, the results could help explain the chicken-and-egg problems of how these crucial biopolymers – which need each other now – could have existed without the other.

Donato Giovannelli is a microbiologist specializing in extremophiles, microbes that thrive in what used to be considered uninhabitable environments. During his EON time his research has taken him to volcanic lakes in Costa Rica and to Iceland to dive for unusual extremophile samples at underwater geothermal vents. He considers himself lucky to have stumbled into the program.

"At most postdoc programs, you usually go to your lab and work on a project that was already there. Here they say 'send us your best ideas' and then 'here is a budget to study them.' You have complete freedom.

"It's quite a place for the right kind of person. There's big freedom, but with it comes big responsibility in terms of showing you're putting the opportunity to good use."

Jakob Andersen is a specialist in the new field of algorithmic cheminformatics, and his goal is to find the formal "grammars" of chemical systems so they can be described in computational terms. To the extent that is possible, much of the by-rote work of analyzing chemical reactions can then be

Jakob Andersen from the University of Southern Denmark used his EON years at ELSI to further his effort to create a kind of virtual chemistry.

done and done quickly by computer. "This is potentially a way to take boring, error-prone mechanical stuff out of doing mass spec [mass spectroscopy] or isotope results because we can predict the results if we get the rules right.

"Chemistry, of course, is vast and tricky, and so those rules are difficult to determine. And the rules for cyanide chemistry, for instance, are not going to be the same as other elements."

Because Andersen's techniques hold out the possibility of better and faster analysis of chemical reactions, the possibilities for collaborations with ELSI chemists and geochemists were many. But what he found was that it takes substantial amounts of time to make a wet-chemistry and computational-chemistry collaboration work – for scientists to understand what other scientists are really saying – and most of his projects were in a beginning stage.

"I was very good for EON because all I need is a computer, no expensive lab equipment," he says. "But also, I think that maybe with my work we needed more time together."

But some of those collaborations have continued since Andersen left ELSI and they remain promising. What's more, Andersen was one of the organizers of an EON workshop on computational chemistry at ELSI in October. The two dozen people present were the primary researchers in the field, and EON was able to bring them all together for the first time.

The field is still in its beginning phase, but EON Director Cleaves – a longtime prebiotic chemist – says he thinks that in twenty years much of what is now wet chemistry will be done via computer. "This is the future of chemistry, and these are many of the people who will create it."

Workshops like that one are an integral part of the EON program and take place all the time. In two years, Cleaves estimates, 500 visitors have taken part in the workshops and annual symposia, many of them top scientists in their fields.

Another way that the success of an institution or program is assessed both formally and informally is whether fellows land jobs in their highly competitive fields. So far, Cleaves says, more than half of the EON fellows have new positions to look forward to, or are already in them.

Katherine Petrie, for instance, is a biologist interested in the role of parasites as a driving evolutionary force during the origin and early phases of our biosphere. Her EON work has been scientifically productive, and she believes it helped her land a tenure-track teaching job at the University of California, San Diego.

"[EON]'s showing the science you produce but also that you can handle a pretty complicated life on two continents, can manage a research budget, and can work well as part of a larger group. Did those things help me get the job? I have to think they did."

The EON grant is coming to an end in early 2018, and it would definitely be a blow to ELSI if it weren't renewed. It fell to Cleaves to oversee the renewal application, and he got the word in late October that ELSI had not made the Templeton cut for 2018.

"They told me it was nothing about our program but rather that they decided to cap their grants at a level below what EON was requesting. It's surely a disappointment, but the program manager said he expects the larger grants to resume next year. He encouraged us to apply again."

ELSI, like any other organism as it grows ever more complex, has to find new ways to survive and prosper. It has to evolve and adapt. Why should an institute be any different?

Stuart Bartlett, Jakob Andersen, and Piet Hut during a weekly EON Science Chat.

Katherine Petrie, an EON biologist and soon-to-be professor at the University of California, San Diego.

ELSI scientists Tomohiro Mochizuki and Shawn McGlynn collecting specimens on a field trip to Shikine-jima in the fall of 2017.

9. Japanese Islands with Early Earth Secrets

Collecting data – whether through lab experiments, stable isotope analysis, modeling, or observation – is at the center of what scientists do. Here is how that's done at ELSI:

Along the edge of an inlet on a tiny Japanese island in the Philippine Sea can be found – side by side – striking examples of conditions on Earth some 2.4 billion years ago, 1.4 billion years ago, and today.

The first example is a small channel with iron-red, steaming, and largely oxygen-free water filled from below with the bubbling liquid above 71 degrees C(160 F). This setting is Earth as it existed, in a general way, as oxygen was becoming more prevalent some 2.4 billion years ago. Microbes exist, but life is spare at best.

Right next to this ancient scene is a region of green-red water filled with cyanobacteria, the single-cell creatures that helped bring masses of oxygen into our atmosphere and oceans. Locals come to this natural onsen for traditional hot baths, but they have to make their way carefully because the rocky floor is slippery with green mats of the bacteria.

Next to that water there is the water of the Philippine Sea, cool but with spurts of warmth shooting up from below into the cove.

All of this is within an area of about 100 square feet.

It is a unique hydrothermal scene, and one recently studied by two ELSI researchers – microbiologist Shawn McGlynn and ancient virus specialist Tomohiro Mochizuki.

They were taking measurements of temperature, salinity, and more, as well as samples of the hot gas and of microbial life in the iron-red water. Cyanobacterial mats were collected in the greener water, along with other visible microbe worlds.

Their scientific goals are to answer specific questions. Are the bubbles the results of biology or of geochemical processes? What are the isotopic signatures of the gases? What microbes and viruses live in the super-hot sections? And can cyanobacteria and iron co-exist?

All the questions are connected, though, within that broader scientific effort to more specifically understand conditions on Earth through the eons and how those conditions can help answer fundamental questions about how life might have begun.

"We really don't know what microbiology looked like 2.5 billion or 1.5 billion years ago," says McGlynn, "But this is a place we can go where we can try to find out. It's a remarkable site for going back in time."

In particular, there are now few natural environments with high levels of dissolved iron like this site has. Yet scientists know from the rock record that there were periods of Earth history when the oceans were similarly filled with iron.

Mochizuki elaborates: "We're trying to figure out what was possible chemically and biologically under certain conditions long ago.

"If you have something happening now at this unusual place – with the oxygen and iron mixing in the hot water to turn it red – then there's a chance that what we find today was there as well billions of years ago."

The Jinata hot springs, as the area is known, is on Shikine-jima Island, one of the farthest out in the Izu chain of islands that starts in Tokyo Bay. More than 100 miles from Tokyo, Shikine-jima is nonetheless part of Tokyo Prefecture.

The Izu islands are all volcanic, created by the underwater movements of the Philippine and Pacific tectonic plates. That plate boundary remains in flux and thus the hot springs and volcanoes. The terrain can be rugged. In English, Jinata translates to something like "Earth hatchet," since the hot spring is at the end of a path through what looks like a large cliff that has been cut through with a hatchet.

Hot springs and underwater thermal vents have loomed large in thinking about origins of life since it became known in recent decades that both generally support abundant life – microbial and larger – and supply nutrients and even energy in the form of electricity from vents and electron transfers from chemical reactions.

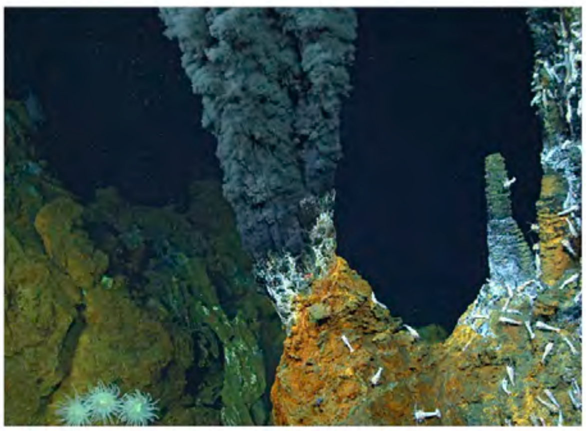
And so, not surprisingly, vents are visited and sampled frequently by ELSI scientists. McGlynn was on another hydrothermal vent field trip to Iceland over the summer with, among others, EON fellow Donato Gionovelli and ELSI principal investigator and electrochemist Ryuhei Nakamura.

McGlynn's work is focused on how electrons flow between elements and compounds, a transfer that is now broadly accepted as a basic architecture for all life. With so many compelling flows occurring in such a small space, Jinata is a superb laboratory.

For Mochizuki, the site turned out to be exciting but definitely not a goldmine. That's because his specialty is viruses that live at very high temperatures, and even the bubbling hot spring in the iron trench measured only about 73 degrees C (163 degrees F.) The viruses he incubates live at temperatures closer to 90 C (194 F), not far from the boiling point.

His goal in studying these high-temperature (hyperthermophilic) viruses is to look back to the possibly earliest days of life forming on Earth using viruses as his navigators.

Since life is thought by some scientists to have begun in a super-hot RNA world, Mochizuki wants to look at viruses still living in those conditions today to see what they can tell us. Some of his findings raise questions about the super-hot RNA world hypothesis because neither he nor other researchers have found viruses present on the RNA of primitive denizens of the Archaean kingdom. The logic is complex, but the results are both puzzling and intriguing to Mochizuki.



Black smoker chimneys spew out water and chemicals as hot as 350 degrees F/ 177 C from deep in the Earth. The fact that many lifeforms thrive in these extreme environments has led some scientists to argue that life began around such hydrothermal vents.

So he is always interested in sampling hot springs and thermal vents to collect high temperature viruses and to look for answers and surprises.

Researchers often need to be inventive on field trips, and that was certainly the case at Jinata. When McGlynn first tried to sample the bubbling water source, his hands and feet quickly felt on fire and he had to retreat. And that was while he was wearing protective boots and gloves.

So he and Mochizuki built

a funnel out of a large plastic water bottle, a device that allowed the bubbles to be collected and directed into the sample vial without the gloved hands being so close to the heat. The booted feet, however, remained a problem and the heat just had to be endured.

Near the hot spring source were collections of what appeared to be fine etchings on the bottom of the red channel. These faint designs, McGlynn explained, were the product of a microbe that makes its way along the bottom and deposits lines of processed iron oxide as it goes. So while the elegant designs are not organic, the creatures that create them surely are.

Filaments at the bottom of the scalding Jinata trench are created by microbes, which build the lines of iron oxide as they pass through. (photo by Marc Kaufman)

"Touch the area and the lines go poof," McGlynn said. "That's because they're just the iron oxide, nothing more. Next to us is the water with much less iron and a lot more oxygen, and so there are blooms of [green] cyanobacteria. Touch them and they don't go poof; they stick to your hand because they're alive."

McGlynn also collected some of what he calls the poofs to get the microbes making the unusual etchings. It could be a microbe never identified before.

As a microbiologist, he is of course interested in identifying and classifying microbes. He initially thought the microbes in the iron channel would be anaerobic. But he found that even a tiny amount of oxygen making its way into the springs from the atmosphere made most of the microbes aerobic.

But it is ultimately that flow of electrons that really drives McGlynn. He even dreams of them at night he told me.

One of the goals of his work is to help answer some of the outstanding questions about that all-important flow of electrons (electricity) from the core of the Earth. The energy transits through the mantle to the surface and then often is in contact with the biosphere (all living things) before it enters the atmosphere and sometimes disappears into space, or else bonds with other elements or compounds.

He likens the process to the workings of a gigantic battery, with the iron core as the cathode and the oxygen in the atmosphere as the anode. Understanding the chemical pathways traveled by the electrons today, he is convinced, will tell a great deal about conditions on the early Earth as well.

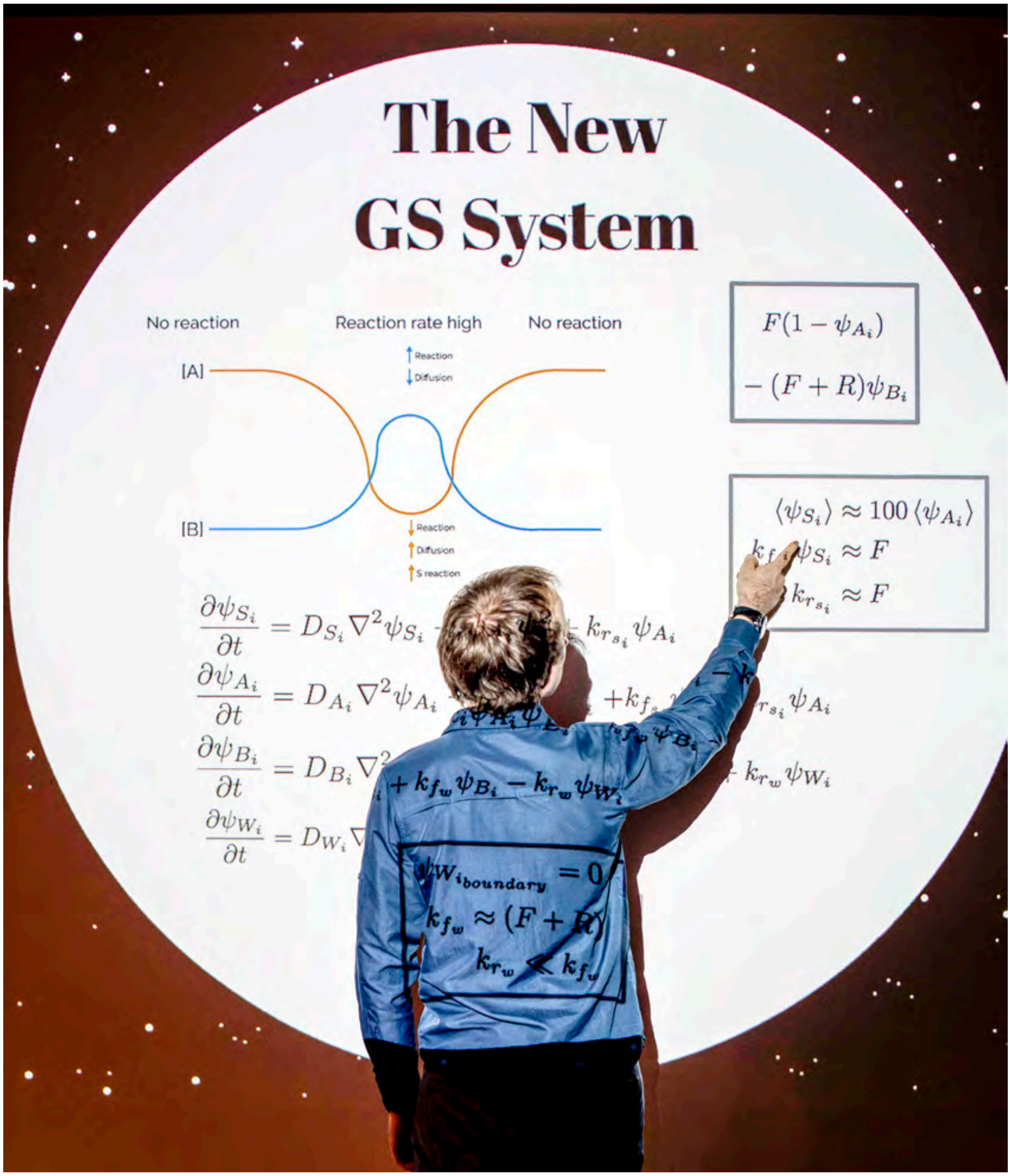
The fieldwork on the island illustrates the hit-or-miss nature of those kinds of outings, which might yield results back in the lab and might not. But McGlynn and Mochizuki did make some immediate and surprising discoveries; the discoveries just didn't involve microbes, electron transfer, or viruses.

During a morning visit to a different hot spring, they came across a team of what turned out to be officials of the Izu islands – all dressed in suits and ties. They were visiting Shikine-jima as part of a series of joint island visits to assess economic development opportunities.

The officials were intrigued to learn what the scientists were up to and made some suggestions of other spots to sample. One was an island occupied by Japanese self-defense forces and generally closed to outsiders. But the island is known to have areas of extremely hot water just below the surface of the land, sometimes up to 100 C.

The officials gave their cards and told the scientists to contact them if they wanted to get onto that island for sampling. And the official from Shikine-jima was already thinking big.

"It would be a very good thing," he said, "if you found the origin of life on our island."



ELSI research scientist Stuart Bartlett specializes in artificial life and complex systems.

10. Theorists Are Essential

ELSI is constantly nourished by lab experiments, measurements, sampling, and modeling – basic science of all sorts. But the agora was built for a specific and essential reason beyond afternoon tea. It was designed as a place for theorists to meet with experimenters and modelers, and it, too, has been well used.

Some of the least-understood though influential scientists in an institute like ELSI are the theorists.

Theorists at the institute include Hut, Nicholas Guttenberg (who also works at a Japanese company trying to understand, among other things, the origin of consciousness), planetary scientist Ida, and geophysical modeler Hernlund.

But the two most often seen in the agora in animated discussion with other scientists are Eric Smith, whose background is in physics and complex systems, and Nathaniel Virgo. It can be difficult to explain precisely what they do and why, but it's not hard to see that they do it well and are widely respected.

Virgo comes from the United Kingdom but before coming to ELSI had been in Tokyo for two years working in Takashi Ikegami's University of Tokyo lab. The two had some of the same interests and scientific inclinations. In particular, they were interested in material systems – like oil droplets – that can be self-moving, even swimming along a pH gradient.

Virgo also has been executive director of EON, and, in that position, he convenes those EON researchers cycling through ELSI for a Monday afternoon science chat. His goal is not only to be of theoretical use to individuals in their research but also to aid in the process of tying together the different disciplines that are often at the table.

"Ideally in science, the cycle is hypothesis, testing, and then getting to another hypothesis. But this coming up with a good hypothesis is really difficult. We at ELSI want to know the origin of life. But how do we even ask the scientific questions in a way that makes sense? This is where theory can be useful."

Shigeru Ida

Virgo's background is in computer science, theoretical ecology, and artificial life. In all three, the goal is to discern the patterns and the rules that make things run, rather than to delve into the specific workings of specific organisms or locales. And, using the same abstract approach to the scientific issues related to origins, he hopes to help tease out useful ways forward for colleagues and himself.

His own work is focused now on possible pathways from geoscience to bioscience. He works at ELSI with chemist-astrobiologist Irena Mamajamov on the "messy" chemistry initiative, an effort to embrace the known complexity of early Earth and to use it as a guide rather than to view it as an obstacle to understanding issues such as how RNA or proteins might first have been formed.

Part of his role is to design computer methodologies to help trace and understand the vast number of chemical reactions potentially underway in these "messy" scenarios. This effort is also a journey into an abstract world where the goal is to identify patterns and processes rather than the specific molecules produced by them, where "broad classes of behavior can arise repeatedly, even in systems that are very different in their microscopic details." Autocatalysis, the enabling of a reaction in which the catalyst is also one of the products of the reaction, is of special interest because with it present, the system can really grow.

Virgo and experimental chemist Cleaves have an experiment underway that speaks to the kinds of reactions that especially intrigue Virgo. The two can't be specific now about their work, but it involves slow chemistry over months or years and looks for unexpected changes of an uncontrolled, "messy" kind.

Virgo's own hypothesis on the origin of life involves "messy" chemistry, followed by less-messy chemistry, leading to "messy" biology that in turn emerges ultimately as less-messy life. Underlying a lot of his thinking is the notion that evolutionary change – which he sees as a pattern begun in the chemical and mineral worlds – is really about what process, or later what organism, is most adept at evolving. It's called the evolution of evolvability.

"The reason for the abstract nature of my work (and I would say of most theoretical work) is that the goal is to try to capture so-called 'universal' phenomena. Understanding these phenomena on an abstract level tells us what is necessary for them to occur, which in turn tells us where to look in order to find them in the real world," he says.

His theorist colleague Eric Smith comes from the world of complexity science and in particular from the Santa Fe Institute, which is a global center for that approach. Smith's formal background is in physics and mathematics, but he is a voracious learner about other fields as well.

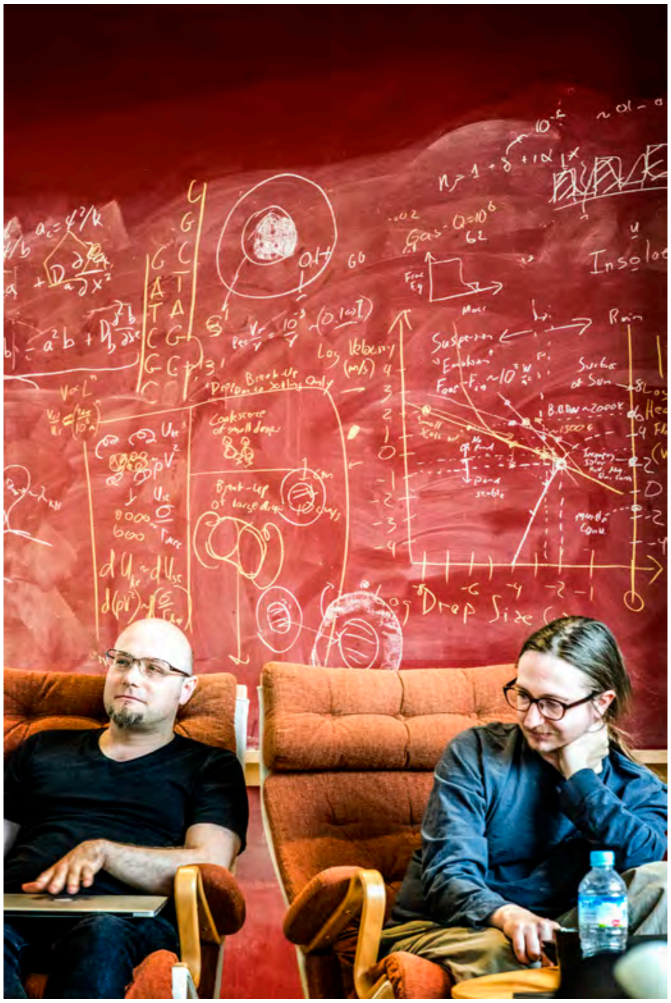
Any number of ELSI researchers will remark, unbidden, about how Smith, who is head of the ELSI Scientific Steering Committee, helped them think more broadly about their own work. (Yuichiro Ueno is one of them.)

Thinking broadly comes naturally to Smith as evidenced by his ELSI work but also by influential talks he has given about, among other subjects, the inevitable emergence of life on Earth. Given the physics and chemistry of the solar system, he argues, the movement towards biology on a planet with the features of early Earth was not surprising and random but rather was predictable.

That particular complex and elegant argument came up during a conversation with Ryuhei Nakamura, an ELSI electrochemist and principal investigator. Nakamura said that he heard Smith's talk (which can be found online) and that it changed the way he looked at his own science.

This kind of interaction, Smith says, is part of what a theorist aims for consciously or instinctively.

"To surprise the mind and bump it into directions that mind might not have gone is historically the way that much



Nathaniel Virgo and Nicholas Guttenberg

Eric Smith

important work gets done," he volunteers. And so Smith is often in the agora or at conferences and workshops talking and listening and seeing if there are perhaps broader ways of looking at a researcher's particular scientific problems (or perhaps his own.)

There are two other ways in which Smith the origin-of-life theorist is quite unusual.

The first is that he does not think that the many fields of science that flow into that specific question – how to explain specifically how life emerged -- have the empirical knowledge yet to provide the material that a theorist needs to work with. This is not a knock on his part; he says the problem is extraordinarily hard.

And as a result, he sees part of his job as a theorist as trying to understand the technical issues of many different fields feeding into the question and then to come up with recommendations to ELSI decision makers about which disciplines are missing at the institute and who might best fill the empty space. His views are valued and not infrequently acted on.

As a specialist in complexity theory, he also instinctively sees the multidisciplinary approach as the most valuable. This is how he explains the problem:

Scientists in their own disciplines "are dogs in fenced yards trying to catch science problems that are like rabbits. If the rabbit goes under a fence, the dog winds up stopping at the fence, which is why it is there."

What happens in complexity science, he says, and is beginning to happen more and more at ELSI, is that "the goal should be to go from one yard to another however long it takes to catch the rabbit."

Smith does his own mathematical and physics work related to origins of life. But his additional theory work at ELSI in practice is a form of community building toward a goal shared by the institute's founders and many other researchers and the administrative staff.

And that goal is to make ELSI a place with the scientific firepower, the culture, the freedom, and the drive to achieve something that is important and inevitably the product of not one mind but many.

11.Change Is in The Air

For an institute focused on origins, it seemed to be in keeping with its spirit to have examined the origins of the institute.

Those early signs and signatures of a new institute in the making are manifested now in an increasingly mature hub for origins of Earth and origins of life research and gatherings. The institute has become something living and organic.

As a way to illustrate the world of ELSI scientists today, some stories follow that will hopefully give a taste of their work. Current work deserves discrete stories about what is happening right now

This exploration of ELSI would also be incomplete without addressing what might lie ahead.

WPI funds continue only until late 2022. Only one WPI institute has won a five-year extension and that is the Kavli Institute for the Physics and Mathematics of the Universe, (IPMU). Of all the WPI sites, ELSI is probably most like IPMU, the only other pure basic science institute. IPMU also is one of the few institutes to win outside funding – from the Kavli Foundation – a goal of the WPI program.

ELSI's host, Tokyo Tech, is committed to keeping ELSI going after those five additional years of the WPI grant, but will the institute grow or shrink in that transition? And a related question: will it be able to expand and win enough outside support to flourish as the world-class origins-of-Earth and origins-of-life institute its founders envisioned?

These are enormous challenges and, inevitably, change is in the air to meet them. What's more, Vice Director Ida is convinced that institutions need a shake-up and a restructuring on a regular basis or else they become staid and conservative. He may well get his wish.

And a driving reason why is that the goal of becoming a premier institution, an important model for Japan and beyond, is definitely within reach of the robust, highly complex system into which ELSI has evolved.

Yuka Fujii . Planetary Scientist

A planetary scientist by training at the University of Tokyo, ELSI project associate professor Fujii is back at ELSI for a second time, after spending two years at NASA's Goddard Institute for Space Studies in New York City. She worked there with 3-dimensional modeling of Earth and exoplanets, and wrote a recently published paper about atmospheric properties of habitable zones around exoplanets of red dwarf stars.

Asked about the relevance of exoplanets to origin of Earth and of life studies, she replied: "I think the exoplanet study is putting the Earth and Earth's life into a much broader context than before. Our desire is to gain insights into the formation and evolution of Earth by looking at the large ensemble of planetary systems. What is the typical amount of water Earth-like planets have? Where did the water come from? What are the compositions of primordial atmosphere? Are our theories about the early and long-term evolution of planets right? Studying exoplanets provides clues to such kind of questions."

ELSI is an Origins Hub

ELSI was but five months old when, in March of 2013, it held its first international symposium on the origins of a habitable Earth and the ensuing origins of life. This was an enormous undertaking for the fledgling staff, but it was also an essential one. Because gathering together scientists from around the world to discuss these topics, and to learn from what is being reported, is one of ELSI's highest callings.

ELSI's sixth annual international symposium is taking place in January and will continue and expand the tradition of assembling a high-profile, international and Japanese collection of origins scientists. Perhaps most important, it will give them three days to not only listen to some pioneering research, but also to discuss and debate ideas and findings with the ELSI staff and community.

The symposium will follow the ELSI Origins Network (EON) annual meeting, which also brings scientists together from around the globe. EON has also sponsored frequent workshops on origns issues, again attracting some of the world's best and brightest.

ELSI and EON together have brought more than 900 official visitors to the campus as part of these meetings and as a broader effort to both introduce origins scientists to ELSI and Tokyo, and to learn from what they have to say.

1.

2.

1. Norman Packard

A complex systems expert, showing a model of his engineering work to University of Tokyo professor and artificial life specialist Takashi Ikegami, as well as to ELSI members Stuart Bartlett and Olaf Witkowski

2. Kei Hirose

advising one of his students.

3. ELSI chemists

looking over data, a common scene in the agora.

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1. Jack Szostak / David Deamer

Nobel laureate and ELSI PI Jack Szostak (right) with biologist David Deamer (left) of University of California, Santa Cruz at an EON's "Reconstructing the Phenomenon of Life to Retrace the Emergence of Life" workshop held in May 2017 at ELSI.

2. Eiko Ikegami

Chair of the Sociology Department at The New School in New York City. She was one of the key speakers at the "Cells to Society" workshop, which looked at the origins of living organisms in nature for parallels and insights into the origins of autonomous entities in culture.

3. Jennifer Hoyal Cuthill / Simon Conway Morris

Palaeobiologist and EON postdoctoral fellow Jennifer Hoyal Cuthill, with her Cambridge University advisor and renowned palaeontologist Simon Conway Morris.

4. Steven Benner / Kuhan Chandru /Sudha Rajamani

Benner, of the Foundation for Applied Molecular Evolution, with ELSI postdoc Kuhan Chandru and chemist/astrobiologist Sudha Rajamani from the Indian Institute of Science Education and Research, at the inaugural workshop "ELSI Origins Network (EON) Strategy for Origins of Life Research."

5. Betul Kacar

Astrobiologist and specialist in molecular evolution, EON Global Science Coordinator and one of the earliest and most frequent visitors to ELSI.

6. Andy Knoll

Professor of biology and of earth and planetary sciences at Harvard University. Knoll is also an Archean era geologist and co-founder of the Origins of Life Initiative at Harvard.

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7. Antonio Lazcano

Evolutionary biologist with the Universidad Nacional Autónoma de Mexico presenting at a history and philosophy of origins research workshop at ELSI. Lazcano served twice as President of the International Society for the Study of the Origin of Life (ISSOL).

8. Masafumi Kameya

A specialist in microbial metabolism and a former ELSI research scientist and now an affiliated scientist, presenting his poster to WPI Working Group for ELSI members at an annual site visit.

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1. Shio Watanabe
2. Maki Akimoto
3. Uika Hosomichi
4. Harumi Tanaka
5. Asako Monica Sato
6. Keiko Matsuura
7. Ayako Tamai
8. Minako Shirakura
9. Ayame Okuyama

ELSI Secretaries and the Art of Japanese Teamwork

For lead secretary Asako Sato, the smooth running of her office – which is so vital to ELSI – can occur only if there is teamwork. In the office, "everyone does everything," she explains, and what she means by that is rather daunting.

At ELSI, secretaries take care of the institute's constant travel needs, they help researchers purchase new equipment, they make complicated lives a little less complex, they keep the ship steady.

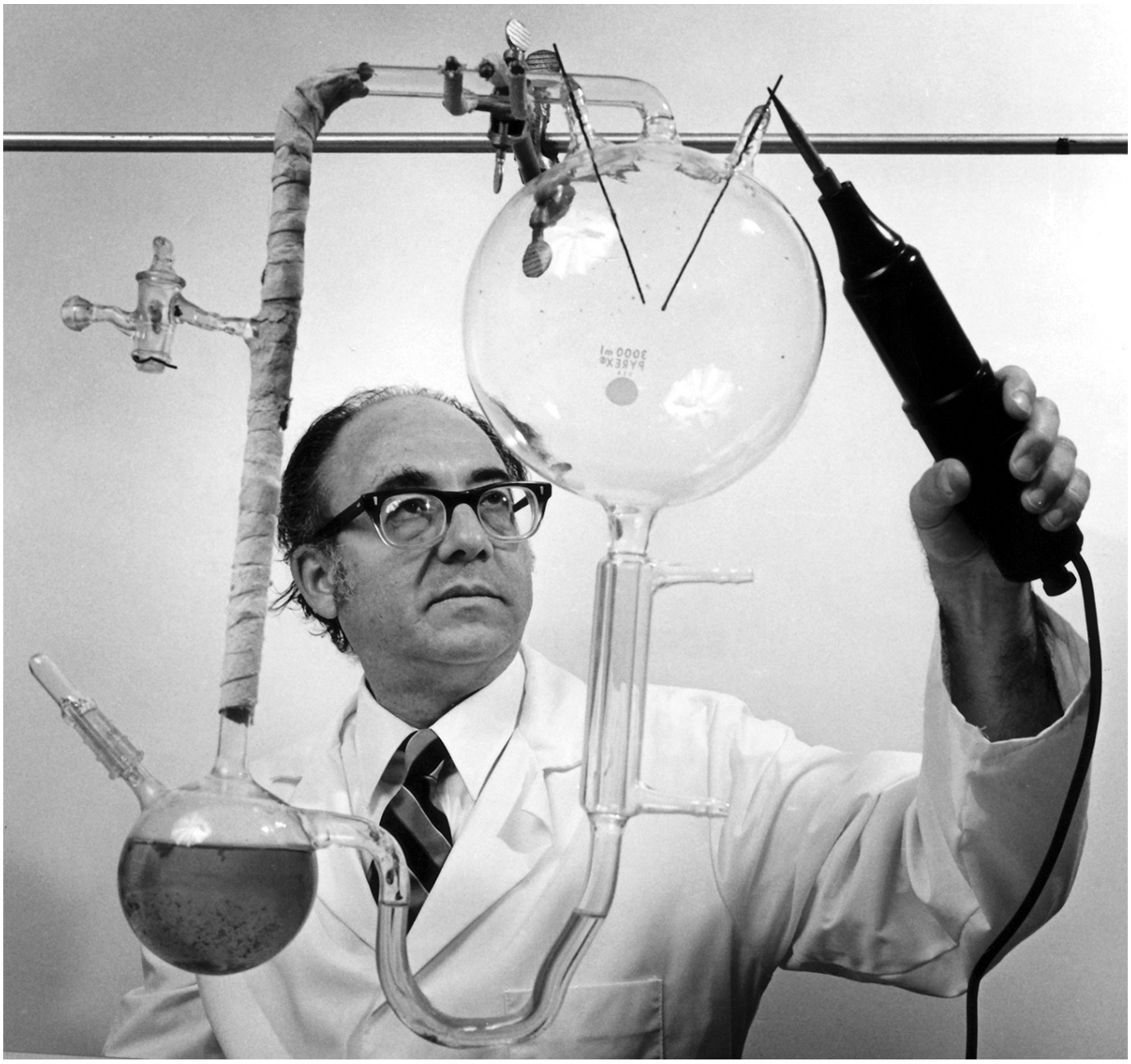
"Everyone has the same goal: support the researchers and make the researchers happy," Sato said. "This is not something you can teach. Our people must have it in their minds."

ELSI has nine full-time secretaries and there is a broad consensus on the campus that they play a major role in creating and maintaining the tangible sociability of the place. Ideas clash all the time at ELSI and sometimes people too. But this happens within an environment that smooths the rough edges.

The team on the second floor that works alongside Sato can claim a good amount of credit for that amicable air and resulting researcher productivity. And while they would never make that claim as individuals they just might as a quintessentially Japanese hard-working team – one that was uncomfortable with the prospect of taking a group photo unless everyone in the office could be present and included.

Lucy Kwok

Illustrator . Language Editor
ELSI



12. "Messy" Chemistry

A New Way To Approach the Origins of Life

More than a half century ago, Stanley Miller and Harold Urey famously put water and gases believed to make up the atmosphere of early Earth into a flask, sparked the mix with an electric charge, and produced amino acids and other chemical building blocks of life.

The experiment was hailed as a ground-breaking reproduction of how the essential components of life may have been formed or at least as a proof of concept that important building blocks of life could be formed from more-simple components.

Little discussed by anyone outside the origins of life scientific community was the fact that the experiment also produced a lot of a dark, sticky substance, a gooey tar that covered the beaker's insides. That residue was dismissed as largely unimportant and regrettable then and in the thousands of parallel origins-of-life experiments that followed.

Today, however, some intrepid researchers are looking at the tarry residue in a different light.

Just maybe, they argue, the tar was equally if not more important than those prized amino acids (which, after all, were hidden away in the tar until they were extracted from it). Maybe the messy tar – produced by the interaction of organic compounds and an energy source — offers a pathway forward in a field that has produced many advances but ultimately no breakthrough.

Those now studying the tar call their research "messy" chemistry, as opposed to the "clean" chemistry that focused on the acclaimed organic compounds.

There are other centers where different versions of "messy" chemistry research are under way — including George Cody's lab at the Carnegie Institution for Sciences and Nicholas Hud's lab at the Georgia Institute of Technology — but the research is probably most concentrated at the Earth-Life Science Institute in Tokyo (ELSI).

There, "messy" chemistry is viewed as an ignored but promising way forward and almost a call to arms.

"In classical origin-of-life synthetic chemistry and biology, you're looking at one reaction and analyzing its maximum result. It's A+B = C+D," says Irena Mamajanov, an astrobiologist with a background in chemistry who is now a principal investigator at ELSI and head of the overall "messy" chemistry project.

"But life is not like that; it isn't any single reaction. They're looking at a subset of reactions, and we ask: 'Why not look at the whole complex system?'"

There's a broader scientific lineage here – researchers have worked with complex systems and reaction systems in many fields, and, in principle "messy" chemistry is the same. It involves taking a systems approach and applying it to that black box period on Earth when nonbiological chemicals were slowly transformed (or transformed themselves) into chemical systems with the attributes of "life."

The "messy" chemistry work is being noticed, and Mamajanov was a featured speaker in the "New Approaches to the Origins of Life" plenary at the 2017 Astrobiology Science Conference in Mesa, Arizona. At ELSI alone, researchers have been working on "messy" chemistry using metals, using electricity, using radioactivity, using computational chemistry, and using analytical chemistry to tease out patterns and structure in tars like those produced by Miller and Urey.

Mamajanov says this "messy" chemistry approach – which she learned to some extent as a fellow at both Carnegie and Georgia Tech — makes intuitive as well as scientific sense because life is nothing if not complex.

Wouldn't it be logical for the origin of life to be found in some of the earliest complex systems on Earth rather than in straight-line processes that progress almost independently of all the chemistry happening around them?

It stands to reason that the gunky tar played a role, she says, because tars allow some essential processes to occur. Tars can concentrate compounds, can encapsulate them, and can provide a kind of primitive (i.e., "messy") scaffolding that could eventually evolve into the essential designs of a living entity.

Astrobiologist and chemist Irena Mamajanov and prebiotic chemist Kuhan Chandru in their messy chemistry garb. Mamajanov leads an effort at the institute to find new "messy" pathways that allowed early Earth chemical systems to become transformed into the chemical building blocks of life through countless and unknown reactions.

It's the structure, in fact, that stands out as a particularly promising aspect of "messy" chemistry. More traditional synthetic biology is looking for simple molecular structures created by clean reactions while "messy" chemistry is doing the opposite.

The goal of "messy" chemists is to see what interesting chemical processes take place within a defined portion of the "messy," complex sample. What surprising compounds or chemical structures might be formed? And how might they shed light on the process of chemical self-organization and, more generally, the origin-of-life question?

In her lab on the basement floor of the ELSI main building, Mamajanov works with colleagues to synthesize her "messy" molecules and push further into understanding their structures, their potential ability to adapt, and their suitability as possible precursors to the RNA and DNA molecules that characterize life.

Her specific area of study is hyperbranched polymers – 3-dimensional, tree-shaped chains of repeating molecules that connect with other similar molecules. The result of the connections is globular, presents multitudes of chemical reactions, and has some hidden and protected spaces inside the globs. Related synthetic or biomimicked chemicals (i.e., modeled on biological compounds and processes) have been used by the drug industry for some time.

With these hyperbranched polymers, Mamajanov has worked to produce pathways within the "messy" systems where the polymers show characteristics of evolvability.

Hyperbranched polymers exist in nature, most prominently in the process that forms petroleum oil but are also made synthetically for research. The tar that Mamajamov makes out of the chemicals is greasy but clear rather than brownish.

Her hyperbranched polymers are synthetic, as are those of noted synthetic-chemists–in-search-of-biology, such as Steven Benner, at the Foundation for Applied Molecular Evolution and Gerald Joyce of the Scripps Institute.

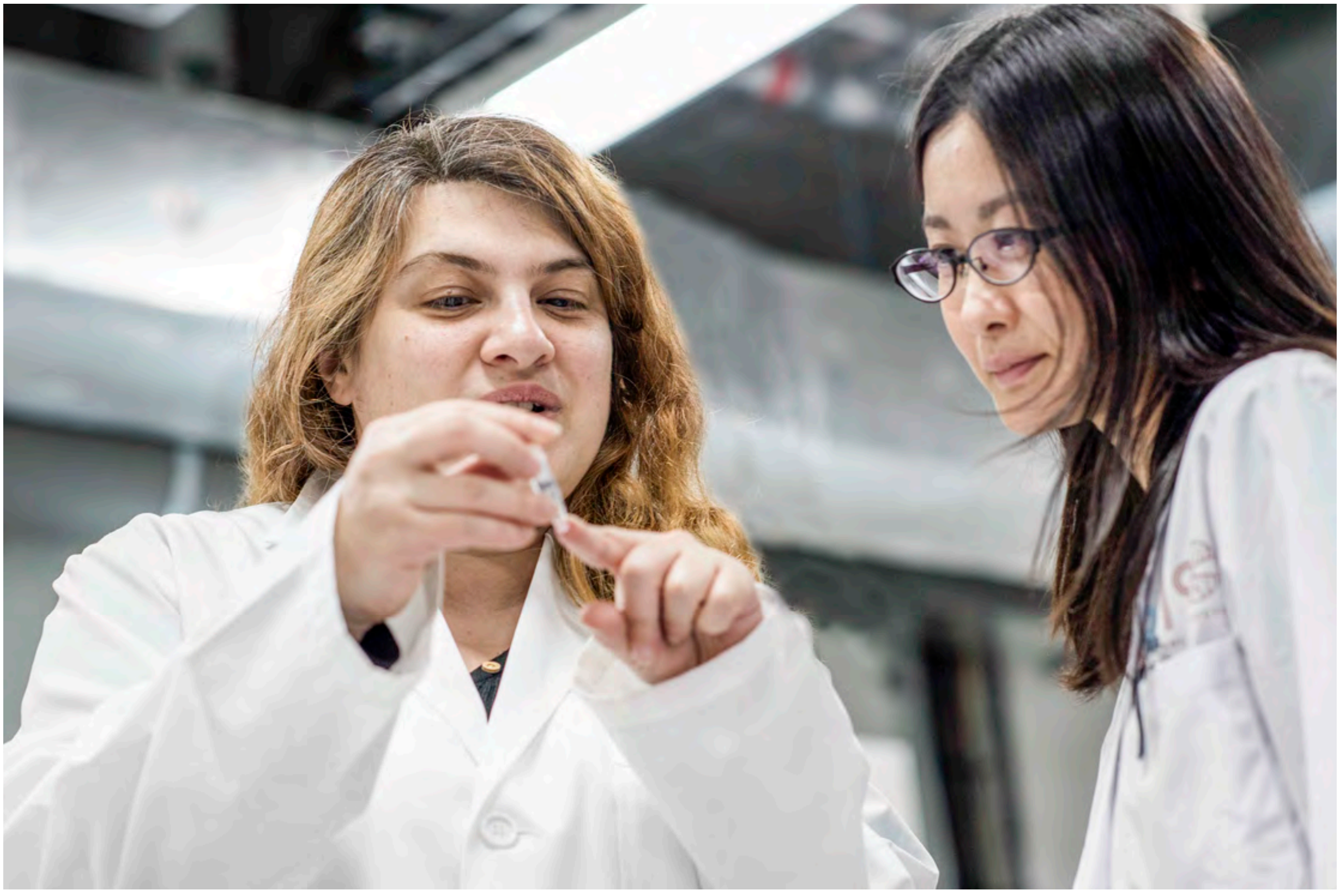
But their starting points are quite different, as are the goals. The two men are working to create clean chemical systems that produce the building-block molecules that they want but without the tar. Mamajamov is intentionally making tar.

Eric Smith, a specialist in complexity systems, physics, and chemistry, who is also at ELSI, sees the "messy" approach as containing the seeds of an important new way forward. "What is now called 'messy' chemistry used to be completely out of the mainstream," he says. "That is no longer the case."

Smith describes how John Sutherland of the Laboratory of Molecular Biology in Cambridge, U.K., won accolades for his work on the prebiotic assembly of important building blocks for RNA using controlled chemistry that avoided all the messiness.

But he was also later criticized for using a such a controlled model – early Earth, after all, did not have any outside controller – and Smith says Sutherland is incorporating the messier side of prebiotic chemistry today, although he still views most tars as impediments.

"Now he's going back to a one-pot synthesis, allowing reactions that would have to be less controlled than what he was doing before," Smith says of Sutherland. "He may do it in a way quite different from Irena and others involved in 'messy' chemistry, but it seems to allow for many more



Irena Mamajanov and Yuki Suna

complex reactions."

And complexity is indeed the desired endpoint. Not simply repetitive reactions and not random ones, but rather reactions that are very complex but ultimately structured.

This search for structure within vast complexity is where another novel aspect of the "messy" chemistry approach comes into play: Mamajanov and others at ELSI are collaborating with practitioners of "artificial" chemistry, computer-simulated versions of what could be happening in "messy" interactions.

That work is being done primarily by Nathaniel Virgo, an artificial-life specialist who uses computing to learn about how chemical systems behave once you leave the laboratory, where the number of chemical components is small and controlled.

His big question: "Are there situations in which you can get 'order from disorder' in chemistry – to start with a 'messy' system and have it spontaneously become more ordered? If so, what kinds of conditions are required for this to happen, and what kinds of ordered states can result?"

Mamajanov needs Virgo's computations to analyze and project what a messy chemical system might do since the sheer number of possible chemical reactions involved is huge. And Virgo needs the "messy" chemistry as a test bed of sorts for his abstracted questions about, in effect, making order out of what appears to be chaos. They are, for each other, hypothesis-generating machines.Virgo pointed to several primary reasons why computational work is important for answering questions about creating order from disorder (and ultimately, he is convinced, life from nonlife.)

"The first is simply that studying 'messy' chemistry experimentally is really hard. If you have a test tube containing a mess, it takes a lot of work to find out what molecules are in it, and [it is] basically impossible to know what reactions are happening, at least not without an enormous amount of work. In contrast, in a simulation, you know exactly what molecules and reactions are present, even if there are millions of different types."

The second reason involves the fundamental issue of studying specific chemical systems versus studying general mechanisms.

"As a complex systems scientist, I first want to know what, in general, is required, for a given phenomenon to occur. Once this is known, it should become clear which real systems will exhibit the right kinds of properties" Virgo says.

"This allows us to narrow down the vast space of possible hypotheses for the origins of life rather than simply testing them one at a time. It should also give us some insight into the question of whether life might be possible with completely different kinds of chemistry than the protein-nucleic-acid-metabolite chemistry we have on Earth."

From his studies he has found that in "messy" chemical systems, chemical self-production occurs and that the systems can change dramatically in response to small changes, such as an increased temperature.

"This suggests that 'messy' chemistry is fundamentally qualitatively different from 'clean' chemistry – adding more species doesn't just mean the system gets harder to study, it also means that fundamentally new things can happen."

And in the origins-of-life world, new things are definitely happening.

Nathaniel Virgo

NASA/JPL

13. Ancient Oceans of Magma

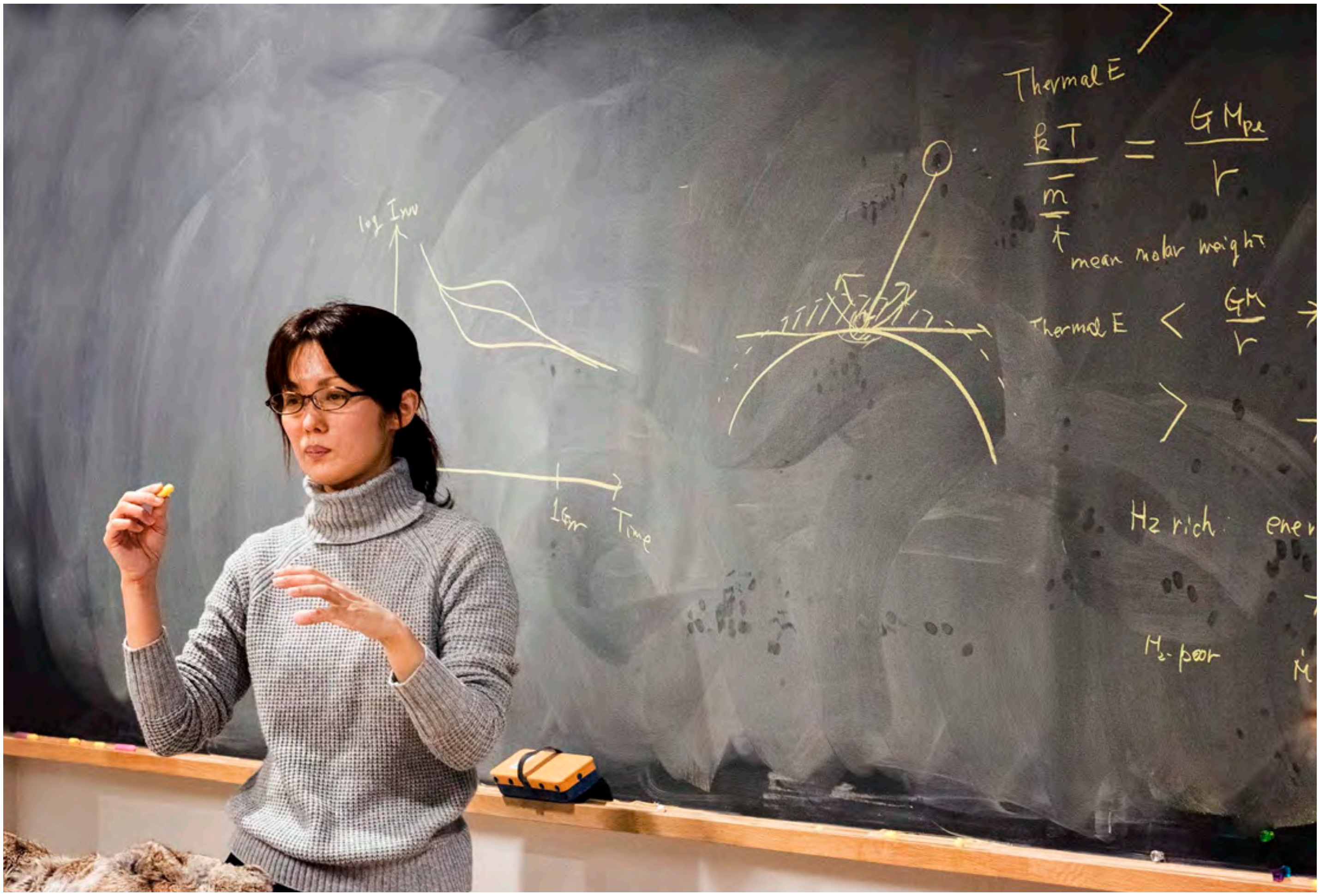
In the late stages of the formation of Earth, the planet was a brutally hot, rough place. But perhaps not precisely in the way you might imagine.

Most renderings of that time show red-hot lava flowing around craggy rocks as meteorites fall and volcanoes erupt. But according to those who study that time, the reality was rather different.

There was most likely no land much of the time, medium-to-large meteorites arrived every few thousand years, and the surface was the consistency of room-temperature oil. Of course it was not oil since this was a preorganic time. Rather, it was mostly molten silicates and iron that covered the Earth in a magma ocean.

At its most extreme, the magma ocean may have been as deep in places as the radius of Mars. And it would have created thick atmospheres of carbon dioxide, silica dust, other toxic gases, and, later, water vapor.

While meteor impacts did play a major role in those earliest days, the dynamics of the magma ocean were determined more by the convection currents of the superhot magma (2000 degrees F and more). Also playing



Keiko Hamano

Scientists are looking more closely at the nature and role of magma oceans in the earliest times of a planet's history. The Earth's oceans of molten rock solidified and degassed in a relatively short time, but did a very long-lasting magma ocean on Venus leave behind its current parched and searing surface?

major roles were the high winds blowing above the surface, the steam atmosphere the magma often created, and, ultimately, by the cooling that over hundreds of millions of years led to the formation of a solid crust.

There is a burgeoning scientific interest in the magma ocean, which is expected to be part of the formation of any terrestrial planet and some lunar formations.

The research focuses on gaining an understanding of the characteristics and diversity of magma oceans and, increasingly, on the potentially significant role a magma ocean plays in the origin of life story on Earth and perhaps elsewhere.

Understanding this early Earth period is so important for a simple reason (i.e., biochemistry) emerged on Earth from geochemistry (i.e., rocks and sediment). Some of the earliest geochemistry occurred in the magma ocean, and so it makes sense to learn as much as possible about the very earliest conditions that ultimately led to the advent of biology.

What's more, scientists believe that magma oceans created the conditions that allowed molten iron to drop down to form the planet's core (necessary for creating magnetic fields), that process resulted in the formation of more complex and thick atmospheres, and those atmospheres produced water cycles. All these planetary changes are seen by scientists as likely pre-conditions for the formation of a habitable planet and for the emergence of life.

So, the magma ocean is a central focus of the unusual origins-of -life institute that I've visited in recent weeks, the Earth-Life Science Institute (ELSI) in Tokyo. While individual researchers around the world work on problems related to the magma ocean, ELSI has put together a kind of critical mass of international scientists of varied backgrounds to take on the subject. That team includes ELSI Vice Director John Hernlund and his wife, seismologist Christine Houser.

Geophysicist Hernlund says that "essentially, magma oceans are the answer to the question of where we came from." And how the planetary evolution that led to life began.

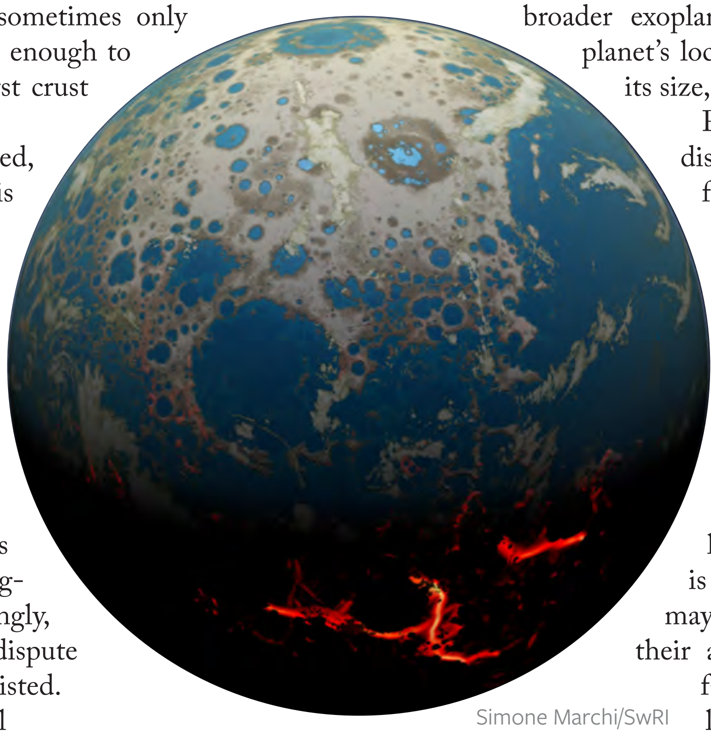
He likens those vast expanses of liquefied metal and rock to a kitchen where meals are cooked from a collection of ingredients.

"If you put some vegetables and meat into a pot of cold water or just let them sit, you're not going to get anything particularly interesting," he says.

"You need the heat, and that's what the magma ocean provides big time," adds Houser.

These molten oceans consisted primarily of metals and silicates along with gases including CO_2, methane, and water vapor, and other trace elements that crashed into the Earth from space. The magma ocean sometimes covered the entire globe, sometimes only parts, and in time it cooled enough to crystallize and form the first crust of the planet.

It should be noted, however, that while there is some agreement among geoscientists about the presence and basic features of an early magma ocean, there is little concrete evidence that proves their conclusions. There are no direct remnants of the magma ocean; only some chemical signatures carry evidence of its long-ago presence. Not surprisingly, there are scientists who dispute that a magma ocean ever existed.

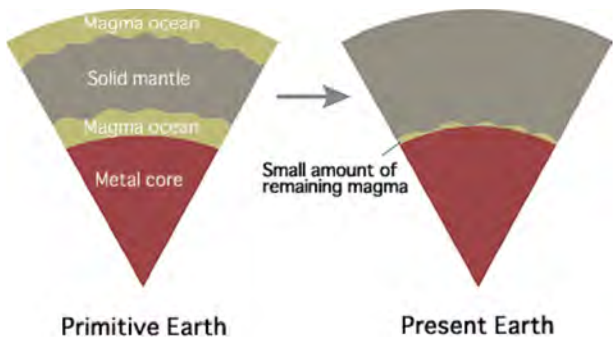


Simone Marchi/SwRI

But there are physical realities that scientists such as Hernlund and Houser say required a magma ocean. The first and foremost is that large, mostly iron core at the center of the planet, the presence of which is not easy to explain without a magma ocean.

Iron is a heavy metal that is thought to have arrived on the proto Earth often mixed with silicon and silicates. Without great heat to melt those elements, the iron would have stayed where it was — mixed among the silicates and other compounds of early Earth.

On the primitive Earth, frequent asteroid bombardments and the heat from formation created a thick magma ocean that extended beneath the solid mantle. It gradually cooled down and probably still remains in a small amount as the ultralow-velocity zones at the bottom of the mantle. (Kei Hirose, Tokyo Institute of Technology)



To deep earth geoscientists like Hernlund and others at ELSI, logic points to a superhot magma ocean that melted the rocks and metals and allowed the heavier liquid iron to sink to the center. Something similar is known to have happened on our moon.

On Earth, enough iron sank to the center to form a core that, in turn, became the crucial heart of the planet's protective magnetic field.

While a magma ocean is a particular and identifiable phenomenon, it by no means exists, behaves, and solidifies the same way on all planets and moons.

Another ELSI research scientist, planetary systems specialist Keiko Hamano, published a paper in Nature that compares the likely magma ocean episodes on two quite similar planets, Earth and Venus. Actually, she also makes broader exoplanetary conclusions based on a planet's location in relation to its host star, its size, and its chemical makeup.

Planets beyond a certain critical distance from their host stars, she found, are expected to have much shorter periods with magma oceans — along the lines of several million years. But those planets within that critical distance can have magma oceans for 100 million years and longer.

Models showed that a striking result of the differing lengths of magma ocean regimes is that however similar the planets may otherwise be, the planets and their atmospheres will have different fates. The ones with shorter-lasting magma oceans are likely to retain whatever water vapor is present in the magma and gradually recycle it to form a water ocean.

The closer-in planets with the longer-lasting magma oceans, however, are likely to lose whatever water they might have initially had as the water molecules are broken apart and the lighter hydrogen floats into the high atmosphere and space. The end result is that the planet becomes desiccated, while remaining a superhot-house because of released water vapor and greenhouse gases in the atmosphere.

This long-ago presence of magma oceans may well explain, or help explain, why Earth is temperate and supports life while otherwise-quite-similar Venus is bone dry and has surface temperatures of 460 degrees C (860 F).

"Atmosphere folks generally don't care about the magma ocean itself, and researchers in magma oceans don't know a lot about the early atmosphere," Hamano told me. "I want

In the Agora, John Hernlund and Christine Houser discuss the seismic and volcanic activity associated with the Ring of Fire.

to connect the two fields because you really can't understand either unless you begin to understand both."

Here's an additional intriguing possibility from Hamano: an enduring puzzle about Venus is that its surface is largely smooth and uncratered. In planetary science terms, that would suggest it is a young planet. But it is not; it was formed at the same time as Earth.

Hamano suggests that the smooth surface may be a function of those connections between the magma ocean and the atmosphere. With the planet unable to lose its heat, the Venusian atmosphere may have kept the planet so hot that the magma ocean survived for as long as 3.5 billion years. And when a meteorite falls into a magma ocean, it leaves no craters behind.

There is also variability in how magma oceans come to be.

Perhaps the most common way is formation via incoming planetesimals, asteroids, or, in the case of our moon, a planet nearly the size of Mars. The impact produces enormous heat, which then radiates outward and perhaps around the entire planet and deep into it.

The early inner solar system had many more flying objects than are found now, and a planet like Earth could have had multiple magma ocean periods, says Shigeru Ida, a planetary formation specialist and vice director at ELSI.

Its magma ocean could also have been formed by an intense greenhouse effect, one created by the release and collection of high-pressure hydrogen in the atmosphere. That process has been proposed as an alternative or corollary to the impact theory — a greenhouse effect so intense that it makes rocks melt.

Ida explains that magma oceans can be formed on smaller objects as well due to the radioactive decay of aluminum-26, an isotope mainly produced in supernovae but prevalent in the early solar system. The heat produced by the radioactivity is believed to be strong enough to have melted rock and separated iron from silicate on small bodies like the asteroids Ceres and Vesta and on some protoplanets.

"We have our ideas about what caused the magma ocean on Earth, but nobody has proof," Ida says. "We know there was great heating and melting and separating of iron and silicates, but in truth we don't know even on Earth if it was from a giant impact or the greenhouse."

Swimming in the magma ocean field need not be limited to our solar system.

Both Hamano (in an Astrophysical Journal paper) and Hernlund say that magma oceans are still being formed in the galaxies all the time and that planets with those oceans can become compelling targets for future direct imaging of exoplanets. The trick would be to look for young stars and the young planets that might orbit them.

The discovery of an exoplanet magma ocean - accomplished through the detection of certain chemical signatures - could provide important insights into the formation of planets today and a most intriguing look into our distant past as well.

14. Radiation, Water, and the Origin of Life

Life on early Earth seems to have begun with a paradox: while life needs water as a solvent, the essential chemical backbones of early life-forming molecules fall apart in water. Our universal solvent, it turns out, can be extremely corrosive.

Some have pointed to this paradox as a sign that life, or the precursor of life, originated elsewhere and was delivered here via comets or meteorites. Others have looked for solvents that could have the necessary qualities of water without that bond-breaking corrosiveness.

In recent years the solvent often put forward as the eligible alternative to water is formamide, a clear and moderately irritating liquid consisting of hydrogen, carbon, nitrogen, and oxygen. Unlike water, it does not break down the long-chain molecules needed to form the nucleic acids and proteins that make up life's key initial instruction manual, RNA. Meanwhile it also converts via other useful reactions into key compounds needed to make nucleic acids in the first place.

Although formamide is common in star-forming regions of space, scientists have struggled to find pathways for it to be prevalent, or even locally concentrated, on early Earth. In fact, it is hardly present on Earth today except as a man-made synthetic chemical.

New research presented by Zachary Adam, an earth scientist at Harvard University, and Masashi Aono, a complex systems scientist at ELSI, has produced formamide by way of a surprising and reproducible pathway: bombardment with radioactive particles.

The two and their colleagues exposed a mixture of two chemicals known to have existed on early Earth (hydrogen cyanide and aqueous acetonitrile) to the high-energy particles emitted from a cylinder of cobalt-60, an artificially produced radioactive isotope commonly used in cancer therapy. The result, they report, was the production of substantial amounts of formamide more quickly than earlier attempts by researchers in theoretical models and in laboratory settings.

It remains unclear whether early Earth had enough radioactive material in the right places to produce the chemical reactions that led to the formation of formamide. And even if the conditions were right, scientists cannot yet conclude that formamide played an important role in the origin of life.

A heavily protected chamber on the Tokyo Tech campus holds a cannister of radioactive cobalt-60, which has long been used for aviation and military research but now is involved in origin of life research.

Still, the new research furthers evidence of the possible role of alternative solvents and presents a differing picture of the basis of life. Furthermore, it is suggestive of processes that might be at work on exoplanets as well – where solvents other than water could, with energy supplied by radioactive sources, provide the necessary setting for simple compounds to be transformed into far more complex building blocks.

"Imagine that water-based life was preceded by completely unique networks of interacting molecules that approximated but were distinct from and followed different chemical rules than life as we know it," says Adam.

Their work was presented at recent gatherings of the International Society for the Study of the Origin of Life and of the Astrobiology Science Conference.

The team of Adam and Aono are hardly the first to put forward the formamide hypothesis as a solution to the water paradox, and they are also not the first to posit a role for high-energy, radioactive particles in the origin of life.

An Italian team led by Rafaelle Saladino of Tuscia University recently proposed formamide as a chemical that would supply necessary elements for life and would avoid the water paradox. Since the time that Marie Curie described the phenomenon of radioactivity, scientists have proposed innumerable ways that the emission of particle-shedding atomic nuclei might have played roles, large or small, in initiating life on Earth.

Merging the science of formamide and radioactivity, as Adam and Aono have done, is a potentially significant step forward, though one that needs deeper study.

"If we have formamide as a solvent, those precursor molecules can be kept stable, a kind of cradle to preserve very interesting products," says Aono, who has moved to Tokyo-based Keio University while remaining a fellow at ELSI.

Aono and technician Isao Yoda in the radiation room with the cobalt-60 safely tucked away.

The experiment with cobalt-60 did not begin as a search for a way to concentrate the production of formamide. Rather, Adam was looking more generally into the effects of gamma rays on a variety of molecules and solvents while Aono was exploring radioactive sources for a role in the origin of life.

The two came together somewhat serendipitously at ELSI, an origins-of-life research center created by the Japanese government. ELSI was designed to be a place for scientists from around the world and from many different disciplines to tackle some of the notoriously difficult issues in origins of life research. At ELSI, Adam, who had been unable to secure sites to conduct laboratory tests in the United States, learned from Aono about a little-used (and free) cobalt-60 lab on the Tokyo Tech campus; they promptly began collaborating.

It is well known that the early Earth was bombarded by high-energy cosmic particles and gamma rays. So is the fact that numerous elements (aluminum-26, iron-60, iodine-129) have existed as radioactive isotopes that can emit radiation for minutes to millennia and that these isotopes were more common on early Earth than they are today. Indeed, the three listed above are now extinct or nearly extinct on Earth in their natural forms.

Less is known about the presence of natural nuclear reactors, sites where a high concentration of uranium in the presence of water has led to self-sustaining nuclear fission.

Only one such spot has been found - in the Oklo region of the African nation of Gabon, where spent radioactive material was identified at 16 -separate sites. Scientists ultimately concluded that widespread natural nuclear reactions occurred in the region some 2 billion years ago.

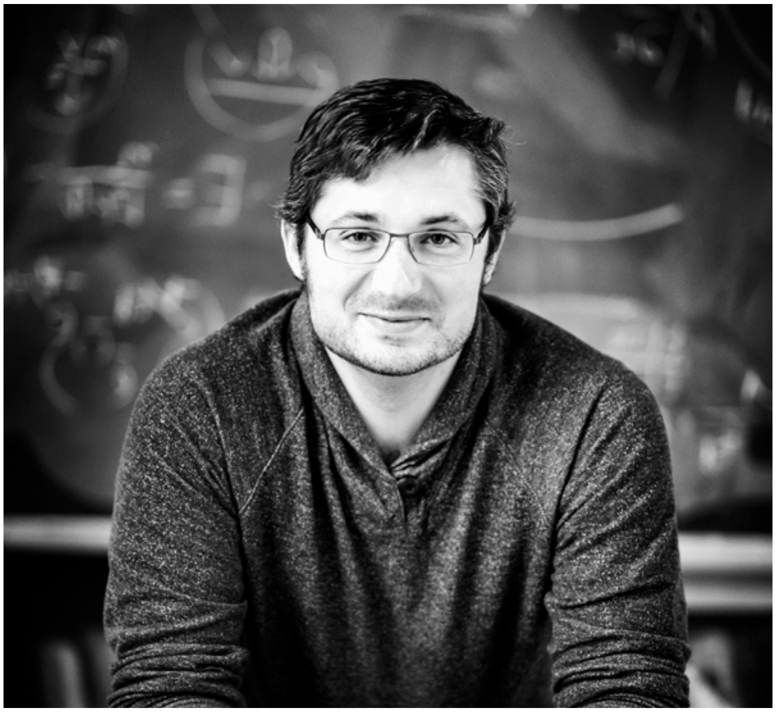
That time frame would mean that the site would have been active well after life had begun on Earth, but its presence is a potential proof of concept of what could have existed elsewhere long before Oklo became radioactive.

Adam and Aono remain agnostic about where the formamide-producing radioactive particles came from. But they are convinced that it is entirely possible that such reactions took place and helped produce an environment where each of the backbone precursors of RNA could readily be found in close quarters.

Current scientific thinking about how formamide appeared on Earth focuses on limited arrivals via asteroid impacts or on the concentration of the chemical in evaporated water-formamide mixtures in desertlike conditions. Adam acknowledges that the prevailing scientific consensus points to low amounts of formamide on early Earth.

“We are not trying to argue to the contrary,” he says, “but we are trying to say that it may not matter.”

But even the presence of a limited number of environments on early Earth may be enough, Adam says, if they are creating significant amounts of formamide over a



Zachary Adam, an earth scientist in the lab of Andrew Knoll at Harvard University.

long period of time through radiolysis. Then an opportunity exists for the onset of some unique chemistry that can support the production of essential precursor compounds for life.

"So, the argument then shifts to how likely was it that this unique place existed? We only need one special location on the entire planet to meet these circumstances," he says.

After that, the system set into motion would be able to bring together the chemical building blocks of life.

"That's the possibility that we look forward to investigating in the coming years," Adam says.

Jim Cleaves, an organic chemist also at ELSI and a coauthor of the cobalt-60 paper, says while production of formamide from much simpler compounds represents progress, "there are no silver bullets in origin-of-life work. We collect facts like these and then see where they lead."

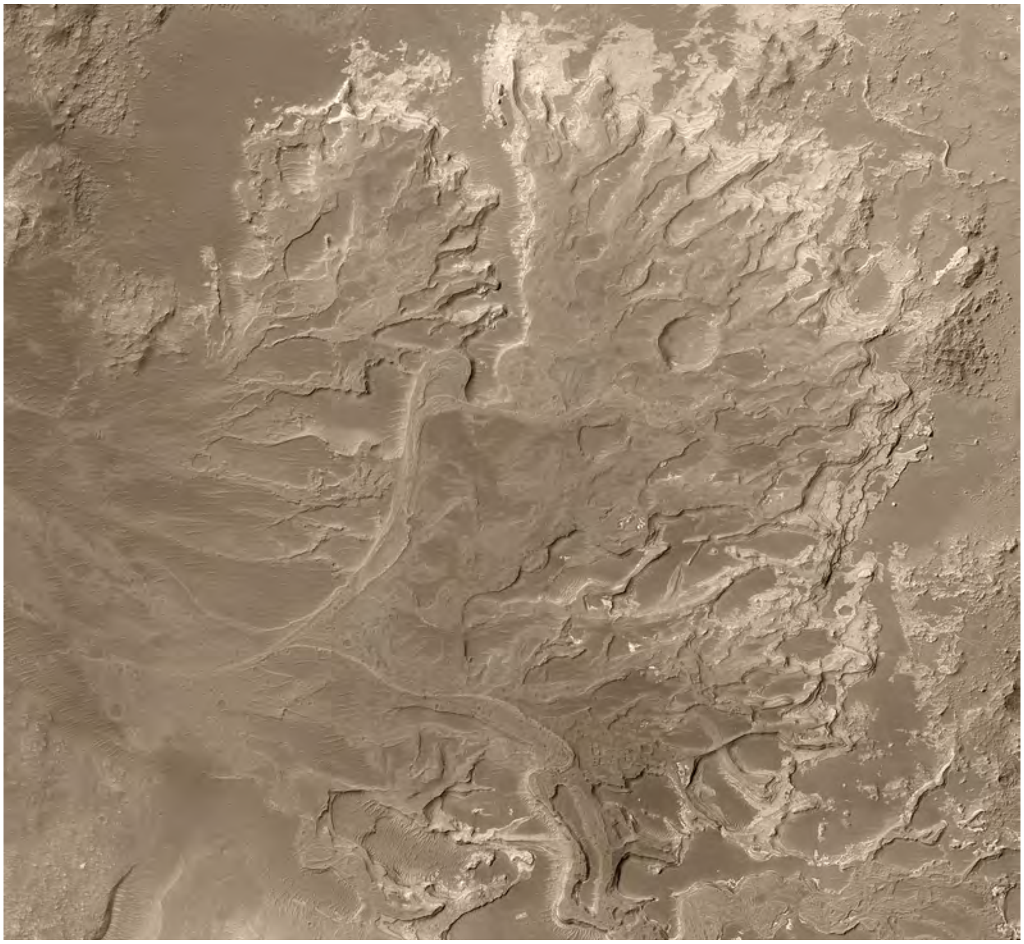
Another member of the cobalt-60 team is Albert Fahrenbach, a former postdoc in the lab of Harvard University's Nobel laureate Jack Szostak and now an associate principal investigator at ELSI.

An organic chemist, Fahrenbach was a late-comer to the project, brought in because Cleaves thought the project could use his expertise.

"Connecting the origins of life or precursor chemicals with radiolysis was an active field back in the '70s and '80s," he says. "Then it pretty much died out and went out of fashion."

Fahrenbach says he remains uncertain about any possible role for radiolysis in the origin-of-life story. But the experiment did intrigue him greatly and led him to experiment with some of the chemicals formed by the gamma ray blasts, and he says the results have been productive.

"Without this experiment, I would definitely not be going down some very interesting paths," he says.



The 70-miles long (113km) Eberswalde Delta on Mars is one of the clearest examples of the fossil remnants of what was once a free-flowing river and its spread onto flat land. The image was taken by the Mars Global Surveyor satellite in 2003 (NASA/JPL-Caltech/MSSS)

16. If Early Mars Was So Cold, Why Did It Have So Much Surface Water

The study of the origins of Earth and life on it – how geoscience became bioscience – used to focus exclusively on our planet. That is no longer the case.

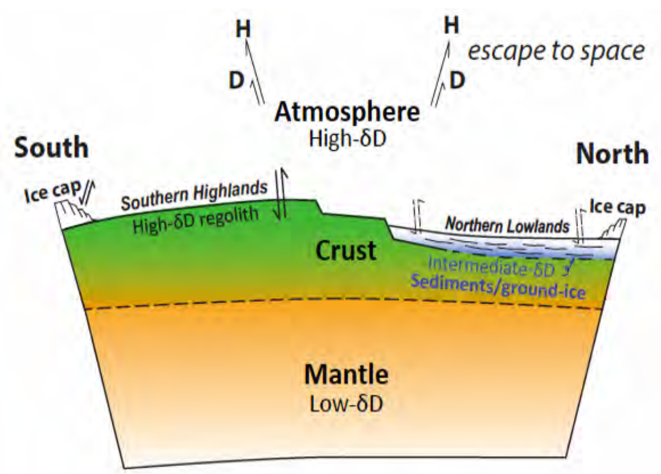
NASA's and other missions to Mars and potentially habitable moons of Jupiter and Saturn and the explosion of knowledge about planets outside our solar system have broadened the origin-of-life field. Now the origins story has also gone extraterrestrial, and an origins institute has to go extraterrestrial as well.

At ELSI, this broadening is apparent in the focus on planet formation and on the oceans of molten rock present on terrestrial planets in their earliest stages. But the new emphasis also includes research on the habitability of early Mars and on how to read the atmospheres of exoplanets.

ELSI's contribution to research into early Mars centers on water and on the key and much-debated question of how much of it might have been present and free flowing on the surface 3 to 4 billion years ago.

ELSI associate principal investigator Tomohiro Usui, an expert in geochemistry and cosmochemistry, has been working for several years on the question of how much water was present on early Mars, which is now bone dry.

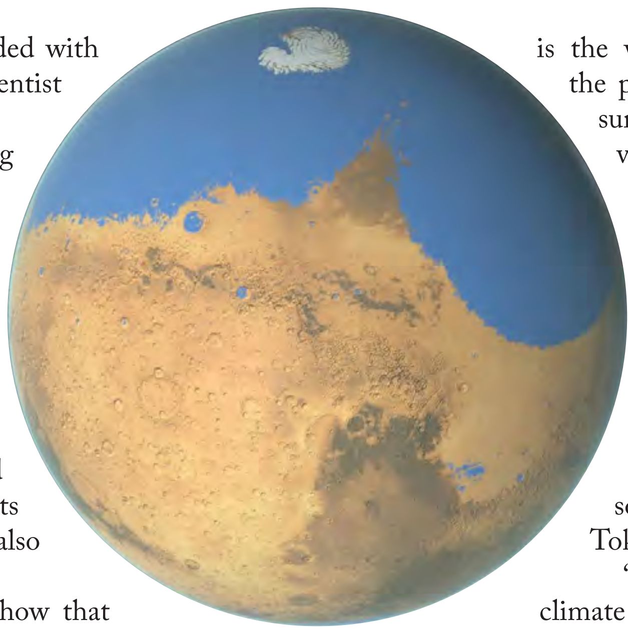
That issue has been addressed by Usui and by colleagues at NASA and elsewhere through the study of isotopic signatures of hydrogen and its heavier form, deuterium, found in Mars meteorites.



Their conclusion: Mars once had a great deal of water, and a substantial amount of it – as much as 90 percent -- remains frozen below the planet surface rather than having been split into hydrogen and oxygen and swept away as the protective atmosphere of Mars disappeared.

That subsurface reservoir holds much of the substantial amounts of water initially present on Mars, Usui says. "Given our data, that had to be the case."

The ELSI effort to understand water on early Mars has been expanded with the recent arrival of research scientist Ramses Ramirez.



A climate modeler specializing in early Mars, he has been actively involved in research that could help resolve one of the most hotly debated issues in early Mars study: the inability to come up with a broadly accepted climate model that would allow for a warm and wet early Mars.

Adding to the difficulty, the unfolding geology, morphology, and geochemistry of Mars is telling scientists it was not only warm and wet but also warm and wet for quite a long time.

Most climate models, however, show that scenario to be a near impossibility. The models, after all, have to take into account that the sun was roughly 25 percent less luminous than now in those early days of the solar system.

This problem became especially acute after not only NASA's Curiosity rover but also Mars-orbiting satellites found ample evidence of a great deal of water on early Mars.

Most recently, the science lead of the Curiosity mission, Ashwin Vasavada, said that there might well have been water at the rover's landing and research site in Gale Crater for up to a billion years – much longer than previously imagined.

Clearly, the models and the evidence coming back from Mars are seriously out of alignment.

Ramirez, formerly a postdoc at Cornell University's Carl Sagan Institute, has spent years trying to come up with a solution, and he is convinced he finally has it.

He says that the release of vast quantities of hydrogen during volcanic eruptions on early Mars (and early Earth, too) could have created a greenhouse effect far different from the largely carbon-dioxide-induced greenhouses most modelers invoke.

The greenhouse that Ramirez puts forward also requires a great deal of CO_2, but the presence of the abundant hydrogen he proposes allows for a more powerful and long-lived greenhouse effect.

"Most of the current models are simply wrong," Ramirez says. "As I see it, the problem is that the assumptions being made are in conflict with geologic observations."

A key factor in his thinking, Ramirez says, is the work of Usui that supports the presence of large amounts of surface water on early Mars. If very large reservoirs of water ice remain below the surface of the planet now, it's only logical to assume that large amounts of surface water were present on early Mars.

Both Usui and Ramirez were familiar with each other's work, and so a collaboration developed soon after Ramirez arrived in Tokyo.

"We hope to reconcile the climate modeling with the water inventory on early Mars, as described by Tomo and geology and geochemistry found on the planet," Ramirez says. "We'll be able to feed off one another on questions like how much water was there and how long did it remain on the surface. We're both interested in the same problem."

Underlying their work is the conviction that studying the possible emergence of life on other planets is now part of the pathway to understanding the origins of life on Earth.

Liquid water is so important to this science because it is viewed as essential to life on Earth and, by inference, most likely essential to life elsewhere because it is such an ideal solvent.

Ramirez says that the debate over water on Mars has taken a most interesting turn of late towards a theory that

was considered highly unlikely just a few years ago. That theory involves the possible existence long ago of an ocean in the northern lowlands of Mars.

That area is one to two miles below the ground level of the southern highlands. This high-low dichotomy, as it is called, has never been explained in a way satisfying to many Mars scientists. While some see the dichotomy as evidence of a long-ago large meteorite hit, others say the northern lowlands show many signs of having been formed by, or filled by, a large ocean.

Ramirez was recently at the Fourth Conference on Early Mars, organized by the Lunar and Planetary Institute and NASA, and he says a possible northern ocean was very much on the agenda to explain what is called the Mars "dichotomy" --- the one to three kilometer difference in elevation between the southern and northern hemispheres.

"The case for a northern ocean on Mars has never been as strong as now," he says. "I heard lots of support for the hypothesis."

The support comes most prominently from those who say the past decade's discoveries of fossil lakes and rivers make it almost necessary that a very large body of water was at the center of a Martian

Mudstone remains of what was once a large lake in Gale Crater, where the Mars rover Curiosity has been exploring since 2112. (NASA/JPL-Caltech/MSSS)

Photo courtesy Ramses Ramirez

Tomohiro Usui

hydrologic cycle. The Earth's rivers and lakes need oceans to supply atmospheric H_2O that will condense, rain down, and then evaporate again. It seems logical now to posit a similar cycle on Mars.

What's more, two recent papers have reported signs of the effects of massive tsunamis near what would have been a shoreline. The absence of a clearly identified shoreline has long been seen as a weakness in the northern ocean theory, and the tsunami remains – if confirmed – could explain why a shoreline is not clearly visible.

Basing his conclusion on climate models and more, Ramirez views the long-ago existence of a northern ocean on Mars as quite likely. Does geochemist Usui share that view based on his work on the Martian water budget?

His reply is that it is surely possible. Whether it was a long-lasting ocean or a more transient large lake remains uncertain, he says with customary scientific caution.

But asked if he agrees with the conclusion of Ramirez and others that the discovery of long-lasting lakes and rivers on Mars requires a hydrologic system with a large body of water, his reply is, "Yes, I totally agree with him."

15.The Rock Library of Ookayama

Stuffed inside two floors of a seemingly forgotten building on the Tokyo Institute of Technology campus – with long grass surrounding it and a small tree growing out of the brick canopy above the entry door -- is one of the premier early-Earth rock sample collections in the world.

You wouldn't know it since the specimens are jammed into what feels like an industrial attic. Clear plastic containers hold the rock samples, and the containers are stored on library rolling storage stacks resting on metal tracks.

There's rock dust in the air and often no place to stand.

Yet all around are rocks that come from the premier geological sites of the world when it comes to understanding early Earth and, potentially, the emergence of life on Earth. They come from Greenland, from western Australia, from the Three Gorges site in China, from northern Canada, from India, and from the floors of several deep oceans.

Shigenori Maruyama began a collection of rock samples from important early Earth geological sites around the world in 1991. The collection is now enormous and housed on the Tokyo Tech campus, but its fate is uncertain.

There's also a collection of zircon crystals from the very earliest days of Earth – the best collection in the world of these essential scientific guideposts, says the library's founder, Shigenori Maruyama - and a collection of 25-meter core samples from China available to slice and analyze for changes over the eons.

Many of the most important discoveries about ancient life in the rock record came from these locales and these kinds of rocks.

They were collected during innumerable expeditions led by Maruyama, a prominent and prolific early-Earth geologist at Tokyo Tech and at the Earth-Life Science Institute on its campus.

"All these rocks, they tell a story," Maruyama says, waving his arm at his now-jumbled domain. "Our goal has been to get samples from around the world, every important site. Then we can see well the stories each sample tells and then what they all tell together.

"Many collections will have rocks, for instance, from Greenland. Maybe one or two or even ten. We have tons of Greenland samples from the prime locations. This is how we are different."

The library is a geological and geochemical treasure chest, but its future is anything but secure. Space is at a premium everywhere in Tokyo, and that reality includes the campus of the Tokyo Institute of Technology. The rock library collection has already had to move once to smaller quarters, and the threat of more relocations remains.

"Yes, we need help," Maruyama says. "Our situation is not stable, and we are trying to make collaborations with geology departments at Harvard University and the University of Cambridge – a global network to share. But this is not an easy task."

This situation is most unfortunate, says Yuichiro Ueno, a former student of Maruyama and now the director of the library. He says that he knows of no other collection like it in the world. It is a large collection (almost 200,000 samples) and many of them with exacting geological and geochemical maps describing precisely where they came from. They form a great resource for scientists around the world, Ueno says, and for young scientists in his lab as well.

"Students who want to work on 4-billion-year-old rocks from northern Canada can find them here. Or if they want samples from the Pilbara section in Australia [another site where very ancient rocks have been found] they are available and well identified, too," Ueno says.

Important results have come from the library collection, and Ueno suggests with a smile that more and, perhaps, more high-profile results are on their way.

The library is also home to a rock that Ueno collected during an expedition to the Pilbara section of Australia, where another scientist discovered one of the earliest samples of Earth rock ever found. Ueno, Maruyama, and others returned to the general area seven times, and Ueno uncovered rocks that appeared to be formed as part of a hydrothermal deposit.

Ueno and his colleagues found a tiny inclusion of fluid in one of the rocks, and testing found that in the fluid were the signatures of the gas methane as produced by early methanogen bacteria. The Pilbara work, which was published in the journal Nature, concluded that the bacteria that lived in that rock did so almost 3.5 billion years ago, making it the oldest signature of a methanogen ever detected.

The collection includes long columns of rock pulled from the ground at the site of the Three Gorges dam in China, as well as specimens collected from the near surface of Greenland, Canada, India, and more.

Are there other important discoveries waiting to be made from the cache of rock samples at Tokyo Tech? Absolutely, says Ueno, and he hopes his students – who are officially associated with ELSI -- will be making some of them.

Ueno says the library is of special importance because the technology for understanding the geochemistry of rock samples is improving and the scientific understanding of what to look for and where is also advancing. So having a large collection of rock samples gathered from most of the important sites of ancient rocks in the world is a unique resource.

And while it may seem that the library has less order than it might ideally, Ueno says significant sections of it are now well catalogued, with samples identified and retrievable via computer.

As both Maruyama and Ueno explain with some passion, Japanese science often flows from its unique setting – surrounded by water and at the meeting point of two underwater tectonic plates. Most plates now have evolved into either underwater or continental plates, but Japan presents a more ancient scenario – the one that many geologists hold existed on the early Earth when there were only islands of rock surrounded by water and with many interacting underwater plates.

There is a famous line of islands east of Tokyo, all formed from volcanoes caused by the pushes and pulls of the underwater Japanese and Philippine plates. Maruyama's doctoral thesis was an exhaustive study of one of those volcanic islands.

Maruyama had no small goal in mind when he started the collection – what he calls a "decoding" through geology of all of Earth's history. His work began in partnership with the Japan Geosciences Union and other international organizations.

Maruyama's most recent rock-collecting trip took place this summer. He and students and postdocs from Tokyo Tech and the University of Tokyo took their equipment to the far-afield and generally off-limits jungle site of the fossil remains of the Oklo natural nuclear reactor in the west African nation of Gabon.

Oklo has been of great interest to Maruyama for years because of his work trying to connect the origins of life to naturally existing radioactivity on the early Earth. For him, Oklo is the proof of concept that such a connection is feasible. Indeed, he is convinced that natural nuclear reactors were widespread on the very early Earth.

The Oklo site was discovered in 1972 by a French team, which was mining for uranium. They were surprised when they found signs that radioactive fission reactions had taken place at that site, and they later found 16 more sites in the area. Those signs included a slightly lower ratio of uranium 235 to other uranium isotopes, which means that the uranium 235 had somehow disappeared.

Within several years it was conclusively determined that natural nuclear reactions had occurred in the uranium deposit and that they probably continued for

Shigenori Maruyama

hundreds of thousands of years.

Because of Maruyama's long years of collecting rocks that could provide insights into the origins of life, the government of Gabon allowed him to come and collect samples.

He has now made three trips to Oklo, spending a month in the country each time. After weeks of mapping and surveying the area by drone, he believes he has found an ideal site to drill down into the Oklo rock. The rock will, Maruyama hopes, tell the geological and geochemical story of how significant doses of radiation can and did change an environment and its biology.

"This is a difficult project and we hope that geologists from other countries will want to work with us," Maruyama says. "It should be very appealing because Oklo is unique in the world as far as we know now."

Maruyama says that his goal, not surprisingly, is to ultimately bring Oklo core samples back to Tokyo Tech and the rock library for intensive study. But whether or not that will be possible remains unclear.

"Most of the uranium was mined by the French or is now depleted of any radioactivity." As a result, he said, the samples will not pose any risk.

But the day the samples arrive in Japan, he acknowledges with a laugh, will no doubt be an interesting one at the customs office.

Yuichiro Ueno